Single-Event Upset Effects in Optocouplers†

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Abstract

Single-event upset is investigated for optocouplers. The threshold LET for optocouplers with internal high-gain amplifiers is very low, causing significant responses even with alpha particles. For heavy particles, the response of the amplifier makes a significant contribution to the total cross section. Charge collection depths in these structures exceed 40 μm. The transient pulse width increases with LET, exceeding 400 ns for very long-range particles above 7 MeV-cm^2/mg.

I. INTRODUCTION

Transients induced in optocouplers by protons have been identified as the cause of anomalies in the Hubble Space Telescope, as reported by LaBel, et al. [1]. In laboratory tests with protons, they observed transients with durations of 20-60 ns in high-speed optocouplers. They attributed the results to transient currents from proton recoil products collected in the large-area photodetector of the optocoupler.

The present paper investigates the effects of heavy ions on optocouplers. Heavy ions produce longer-duration transients than those from short-range proton recoil ions. Mechanisms for the response are investigated, and it is shown that although charge collected in the photodiode is important, a significant part of the total cross section arises from transients in the high-speed amplifier. The threshold LET is much lower for optocouplers with such amplifiers compared to those with basic transistor amplifier circuits. The results show that the charge collection depth is far greater than that assumed in the earlier work, and that gain, rather than response time, is the main reason for the extreme sensitivity of the devices with internal amplifiers.

Three types of optocouplers were studied: the 6N134 (essentially the same as the HCPL-5631 used in the Hubble Space Telescope application); the HCPL5203, which uses an input amplifier with improved sensitivity (lower minimum LED drive current) compared to the 6N134/5631 series of devices; and the 6N140, which uses only a simple (Darlington) transistor amplifier. All of the HP devices use a GaAsP LED with a wavelength of 700 nm. Diagrams of the two basic HP structures are shown in Figure 1. They are fabricated in a sandwich configuration with the LEDs mounted on a separate substrate above the silicon die, providing more consistent optical coupling than laterally coupled optocouplers.

For heavy-ion tests, the LED assembly was removed from all three structures in order to allow heavy ions to penetrate the silicon subassembly.†† Optical coupling material that remained on the silicon die after partial disassembly was removed with a solvent before testing. In addition to the three HP devices, special charge collection measurements were done on 4N49 optocouplers, which provide direct access to the input phototransistor. The 4N49 uses a lateral structure [2], with a longer wavelength LED (890 nm). Table 1 summarizes the characteristics of the devices that were tested.

Table 1. Properties of the Optocouplers

Type	Wavelength	Input Current	Internal Circuit	LET Threshold [MeV-cm^2/mg]
5203	700 nm (GaAsP)	0.5 mA	High-gain amplifier	0.3
6N134	700 nm (GaAsP)	3 mA	High-gain amplifier	0.3
6N140	700 nm (GaAsP)	10 mA	Darlington transistor	11
4N49	890 nm (AlGaAs)	1 mA	Single transistor	---

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††With the LED assembly removed, it is only possible to test the device in the "off" state. This is normally the most sensitive condition unless the LED is driven at very low currents.

All three Hewlett-Packard devices have photodiodes with nearly identical area (approximately 1.3×10^{-3} cm^2). For the 6N140, the diode occupies most of the chip area. For the 5203 and 6N134, the combined areas of the amplifier and output driver are slightly larger than that of the photodiode.

Most of the single-event upset testing on the partially disassembled optocouplers was done at the Brookhaven National Laboratory Van de Graaff. During these tests, each transient waveform was captured with a digital oscilloscope, providing a way to analyze each waveform in detail and also assuring that the cross section was not influenced by noise or short-duration transients. The flux was less than 5000 ion/(cm^2-sec) in order to eliminate potential interference from multiple ion strikes. Five volts was applied to each of the HP devices during testing, using a 2 mA load condition. A limited set of tests was also done at the Texas A&M cyclotron, including charge collection measurements of the 4N49. Ions from the latter facility have considerably greater range than ions at BNL. Tests were also done using ^{252}Cf and laboratory alpha particle sources.

II. TEST RESULTS

A. *Results for Heavy Ions*

The two optocouplers with internal amplifiers produced transients with far longer duration during heavy-ion tests compared to the proton test results reported last year [1]. Figure 2 shows the dependence of pulse width on linear energy transfer for the 6N134. Both the mean values and the dominant pulse width (assumed to be due to ions striking the photodiode region) are shown. At low LET, the pulse width increases abruptly, with an amplitude that is initially below saturation, but gradually increases to the full logic level (5 V). At approximately 1 MeV-cm^2/mg the output transient reaches maximum value, and although the slope continues to increase with increasing LET, the slope is much less than in the region prior to saturation.

There is an additional change in slope for LETs above 10 MeV-cm^2/mg. This is caused by the superposition of the photodiode response with the response of the amplifier. When irradiations were done at angles a "double pulse" sometimes occurred, a narrow pulse and a wider pulse that occurred slightly afterwards. The wider of the two pulses had the same pulse width that was attributed to the photodiode during irradiations at normal incidence. The occasional "wide" pulse width was simply a filling in of the two responses due to diffused charge from the photodiode. In limited tests at Texas A&M, pulse widths up to 400 ns were occasionally observed at an LET of 7 MeV-cm^2/mg; the range of the ions in those tests exceeded 200 μm.

Figure 3 shows how the distributions of pulse widths change when different ion types are used. At low LET, nearly all of the pulses occur in a very narrow range of values, with a slight "tail" in the direction of lower pulse widths. This is consistent with charge collection from the large area photodiode; the "tail" is expected because charge can be collected by diffusion when ions strike regions beyond the periphery of the diode, with less charge compared to ions that strike the physical region of the diode and pass through the depletion region. However, even at 2.1 MeV-cm^2/mg there are a small number of pulses with shorter pulse width, indicating the presence of a second mechanism, associated with ion strikes on the high-gain amplifier. At higher LET values, the "tail" associated with the dominant response increases, along with the relative number of pulses from the second distribution (shorter pulse widths). This trend continues as the LET increases, which is the reason for the difference in the mean and dominant distribution values of pulse width shown in Figure 2. The pulse width histograms imply that the diode contribution only dominates the response at low LET.

The dependence of cross section on LET is shown in Figures 4 and 5 for the two optocouplers with high-gain internal amplifiers. The threshold LET is very low, approximately 0.3 MeV-cm^2/mg. The cross section rises abruptly to values somewhat above the physical area of the photodiode. This, in combination with the pulse width distributions, indicates that charge diffusion makes a significant contribution to the cross section. This is further corroborated by examining the two data points with LET values of 16-18 MeV-cm^2/mg. Note the large difference in cross section. The range of the ion with the open symbol was 39 μm; the other had a range of 60 μm. This provides evidence that charge collection occurs over a very deep region of the device, well beyond that observed for more conventional devices.

The 6N140 has only a basic transistor amplification stage (see Figure 1). The 6N140 exhibited a very abrupt cross section, with a threshold of about 11 MeV-cm^2/mg, as shown in Figure 6. The threshold was more than an order of magnitude higher than that of the more complex optocouplers that contain a high-gain amplifier. The pulse width distribution of the 6N140 was very narrow, consistent with expectations for a basic optocoupler where there is no high-gain amplifier. Thus, the simple transistor amplifier of the 6N140 does not contribute to the cross section. The amplitude of the transient pulses was 100-800 mV, less than 20% of the power supply (logic) level with a 2 mA load condition. The maximum cross section observed for the 6N140 is much smaller than the photodiode area, and depends on load conditions. With 2 mA, the charge induced by ions with LET up to 40 MeV-cm^2/mg is barely large enough to begin to turn on the device.

B. Results on Partially Shielded Units

Tests were also done with a shield that prevented ions from striking regions of the circuit beyond the photodiode. This allowed the contributions of the photodiode and amplifier to be identified by comparing shielded and unshielded results. Pulses with lower amplitude (see the histograms in Figure 3) no longer occurred when the shield was in place. The cross section due to the diode contribution was slightly lower, due to partial occlusion of the photodiode when the shield was in place.

C. Results with Laboratory Alpha Sources

Measurements were made with two laboratory sources, ^{148}Gd, which produces 3.2 MeV alpha particles, and ^{208}Po, which produces 5.1 MeV alpha particles. At the surface, the LET of the Gd source is nearly unity, while the LET of the higher energy Po source is 0.7 MeV-cm^2/mg. The range of these particles are 11 µm for the 3.2 MeV Gd, and 24 µm for the 5.1 MeV Po. Figure 7 compares the pulse width of the response of the 6N134 for the two alpha particle sources with that of long-range ions (during tests with the accelerator). For the alpha sources, the pulse width *decreases* with increasing LET; the pulse width for both sources is also substantially below that obtained with the long-range ions.. The pulse width with the Po source is about 60% greater, nearly identical to the ratio of the energy of the two alpha sources. This shows that it is the energy (essentially deposited charge) of the alpha particle, not the LET in the first few microns that determines the device response. This provides further evidence that charge collection occurs over an extended distance in these structures.

III. CHARGE COLLECTION

The photocurrent produced by heavy ions was measured with the 4N49 optocoupler, which provides direct connection to the diode and transistor. These results are shown in Figure 8. Note the very long duration of the transient response. The effective charge collection depth of this device is 44 µm, (obtained by comparing the total charge with the charge density of the ion used in the experiment). Most of the charge is collected during the first 200-500 ns. As the LET increases, the time at which the current falls below a specific threshold condition (such as the threshold for a high-gain amplifier) extends out in time, consistent with the results for the more complex optocouplers. Thus, the gradual increase in the width of the dominant response, associated with the photodiode component to the cross section, is consistent with the charge collection measurements which show that charge is collected over extended time periods.

Spreading resistance measurements were used to determine the doping concentration and underlying structure of the optocouplers. Figure 9 shows the doping profile of the photodiode region used in the 6N134; the same structure was used for all three Hewlett Packard devices. Both the shallow p-region at the top surface and the substrate are connected to ground. Thus, during normal operation there are actually two depletion regions, one near the surface, and one between the n-region and the substrate, which begins approximately 9 µm below the surface. Charge from heavy ions will be collected from both regions, and charge collection from the second depletion region will extend far into the substrate.

The photodiode structure was analyzed with the PISCES device analysis program to determine how charge collection in the Hewlett-Packard devices compared with the measurements that were made on the 4N49. Those results showed that charge collection occurred far below the substrate, with essentially the same response. Our PISCES analyses also showed that the contact to the photodiode, which occurs at the periphery, did not affect the magnitude or time response of the collected charge.

IV. DISCUSSION

A. *Response Mechanisms*

Optocouplers are relatively simple devices. The input photodiode of all three HP devices has a relatively large area (~10^{-3} cm^2), and near the threshold LET the response of the optocouplers is dominated by charge from the photodiode. However, at higher LET values other regions of the device, associated with the complex input amplifiers, appear to make a significant contribution to the cross section. This is consistent with the complex responses of single-event transients in linear integrated circuits [3-5].

The structure of the diode region, the significant decrease in cross section for ions with 39 and 60 μm range, and direct measurements of charge from the 4N49 photodiode with long range ions all support the conclusion that diffused charge is an important contribution to the total cross section. It is also consistent with the diffusion length of minority carriers in p-silicon with a doping level of 10^{15} cm^{-3}. The effective charge collection depth for these devices appears to be in the 40-60 μm range. Computer calculations of the time response of diode structures with similar doping levels by Dodd, et al. have shown that a significant fraction of the diffused charge is collected in time periods below 150 ns when long-range ions are used[6].

It is possible to estimate the critical charge and the effective charge collection depth from the data obtained with alpha particles and heavy ions, assuming that charge collected in the photodiode dominates the response. Assuming that all of the charge from a 3.2 MeV alpha particle (11 μm range) is collected by the photodiode, the pulse width of the 6N134 is 40 ns (see Figure 7). Thus, a charge of 0.14 pC will produce a 40 ns pulse. The same pulse width will occur for a long-range particle with LET = 0.3 MeV-cm^2/mg. Our PISCES simulations show that 95% of the charge from a long-range ion will be collected within 40 ns. Assuming that the optocoupler amplifier is charge dependent in this region (which is just above the response threshold), then the same charge will be required to produce the same pulse width from short and long range ions. The effective charge collection depth for long-range ions is then 49.1 μm. This result, which is based on experimental measurements, is also consistent with the charge collection depth obtained in PISCES simulations.

B. *Amplifier Responses*

As shown by the histograms in Figure 3, the net response of these devices depends on the response of the amplifier to charge collected at sensitive nodes within the amplifier as well as charge collected in the photodiode. The response of the amplifier only becomes important for LET values above 2 MeV-cm^2/mg. For heavy ions with high LET, amplifier responses will actually dominate the response and extend the pulse width to much longer values. The amplifier contribution must be considered when interpreting responses from protons, as discussed below.

C. *Response in Proton Environments*

We did not measure the responses of these devices to protons. However, the new results with heavy ions and the analysis of charge collection in these structures can be used to interpret proton test results reported last year by LaBel, et al. for the HCPL-5631 [1], which is essentially identical to the 6N134 (except for package type). Their experiments with different incident angles showed that there was a sudden increase in the proton cross section for incident angles above 80°. The cross section at large angles increased by about a factor of ten compared to the cross section at lower angles. They assumed a very shallow charge collection depth in their analysis, which implies a much steeper angular dependence at angles near 90° than they observed experimentally. They noted that the cross section did not increase sufficiently to be entirely due to direct ionization.

Our heavy-ion measurements show that the charge collection depth for long-range particles is about 50 μm. However, the charge collection depth for short-range particles is expected to be much less. Note, however, that the optocoupler amplifier produces pulses between 20 and 200 ns in width, implying that it is sensitive to charge collected over a much longer time interval than in conventional digital circuits.

A series of PISCES simulations were done to determine how the photodiode will respond to recoils that traverse regions well outside the depletion region. Figure 10 shows how the collected charge is affected by track position. A 3.5 μm track with a charge density of 0.1 pC/μm was placed at four different locations outside the depletion region of an n-p diode. At short times, very little charge is collected when the track is not close to the depletion region, but that is not the case for longer time periods where a significant amount of charge is collected by diffusion. At 20 ns nearly ½ the total charge is collected for a track centered at 19 μm, 9 μm beyond the edge of the depletion region. Extending the charge collection to 40 ns allows nearly 70% of the charge is to be collected by an ion at the same location. Thus, although the charge collection depth for short-range particles is clearly less than for long range particles the simulations show that the total charge collection depth – including the top region of the diode – is about 25 μm for time periods of 40 ns, nearly ½ the charge collection depth for long-range particles, and about 10 times thicker than the charge collection depth assumed by LaBel et al. [1].

The revised charge collection depth changes the geometry of the charge that is contributed by direct ionization. The charge collection depth at normal incidence is almost exactly 1/10 the diameter of the photodiode. Let us assume that the increase in cross section at large angles is due to the superposition of a weaker direct ionization component (which will occur for each proton, not just those that interact with the lattice to produce recoils) with charge from the proton recoil. For 60 MeV protons, the maximum recoil energy is about 8 MeV. There will be a continuous distribution of recoil energies [8,9]. As shown by our alpha particle results, the threshold energy for transients in the 6N134 is about 3 MeV, corresponding to a critical charge of approximately 0.14 pC. The charge collected from the direct ionization component of a normally incident 60 MeV proton is 0.004 pC, about 3% of the critical charge. At 80°, the direct ionization component has increased to about 0.024 pC, approximately 20% of the critical charge; the total path length is 60% of the diameter of the diode. Figure 11 shows how the charge from direct ionization is affected by incident angle for the shorter charge collection depth assumed in Reference 1 and the longer charge collection depth based on the present work. The angle dependence (ultimately limited by the diameter of the photodiode) is much more gradual for the longer charge depth, and is less than the critical charge even at 90°.

For 60 MeV protons, charge from direct ionization cannot cause upsets in the optocoupler (however this may be possible with protons of lower energy which have higher LET). The effect of direct ionization is to provide an incremental increase to the total collected charge beyond the contribution from proton recoils; the magnitude of this component depends on the incident angle of the proton. The net effect on the cross section is complex, and must consider the distribution of proton recoil energies as well as the charge collection geometry. Figure 12 shows how the fraction of recoils is affected by direct ionization. A relatively small "shift" due to the incremental increase in charge from direct ionization makes it possible for recoils with significantly lower energy – and increased abundance – to cause the device to respond. This results in a much larger increase in the number of recoil atoms that can cause the device to respond than one would normally expect from such a small change in collected charge. Note however that the net effect on the cross section is somewhat lower than would be predicted from the distribution of recoils alone because the solid angle for the direct ionization component is reduced at large incident angles.

V. CONCLUSIONS

The very low threshold LET and relatively high cross section of optocouplers with complex internal amplifier stages results in error rates from GCR (solar minimum) that are about 0.25 upsets/day. They are far greater than the upset rates expected for most linear integrated circuits. Error rates for simpler types of optocouplers (such as the 6N140) are more than two orders of magnitude lower, primarily because there is no high-speed high-gain amplifier, and the threshold LET is thirty times higher. Although optocoupler transients will not always cause operational difficulties, the pulse width of these devices when they are irradiated with heavy ions is much longer, with full (saturated) amplitude, than test results with protons [1]. Thus, in most cases logic circuits driven by these optocouplers will respond to nearly all of the pulses produced by heavy ions if they are used in asynchronous applications. The response of optocouplers to heavy ions is a potentially severe problem that needs to be carefully considered in space applications.

Although one would normally expect that transients in these devices would be dominated by the large-area photodiode, the test results show the presence of a second component, associated with the high-gain amplifier, that can extend the pulse width to much longer time intervals for LETs above 10

MeV-cm^2/mg. The ion range must be greater than 50 µm in order to approach the equilibrium pulse width for transients in these devices. The presence of the second component results in a complex distribution of pulse widths for these devices, much like that of transients in other linear circuits.

Although the two optocouplers with high gain amplifiers were far more sensitive than more basic optocouplers with simple transistor amplifiers, other types of optocouplers are available with considerably more optical sensitivity. Such devices will likely be even more sensitive to transients from protons and heavy ions, and this needs to be considered when selecting optocouplers and related optoelectronic devices for space applications.

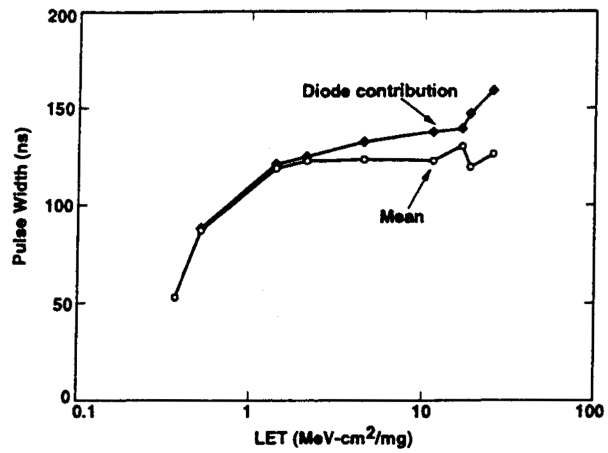

Figure 2. Dependence of 6N134 Pulse Width on LET

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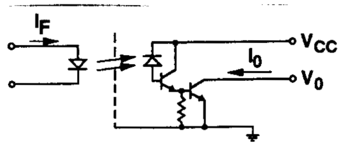
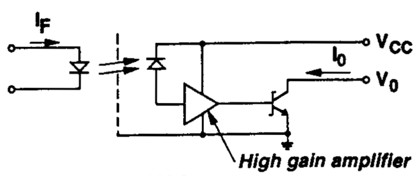
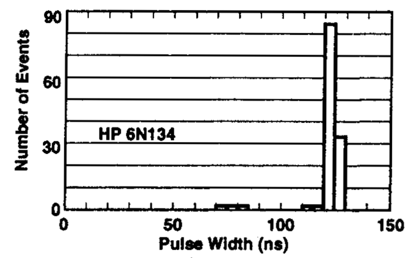


(a) 6N140

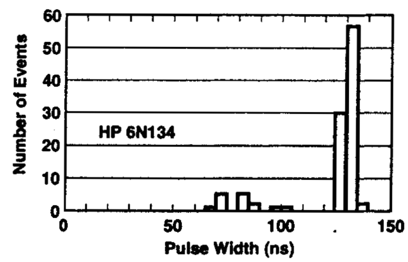


(b) 6N134

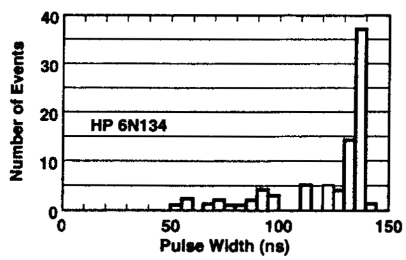
Figure 1. Basic Configurations of Hewlett-Packard Optocouplers



(a) LET = 2.1 MeV -cm^2/mg



(b) LET = 4.5 MeV -cm^2/mg



(c) LET = 11 MeV -cm^2/mg

Figure 3. Distributions of Pulse Width for Ions with Different LETs

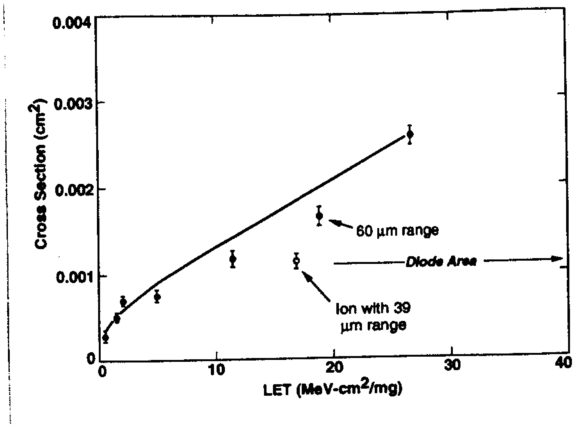


Figure 4. Cross Section vs. LET for the 6N134 Optocoupler

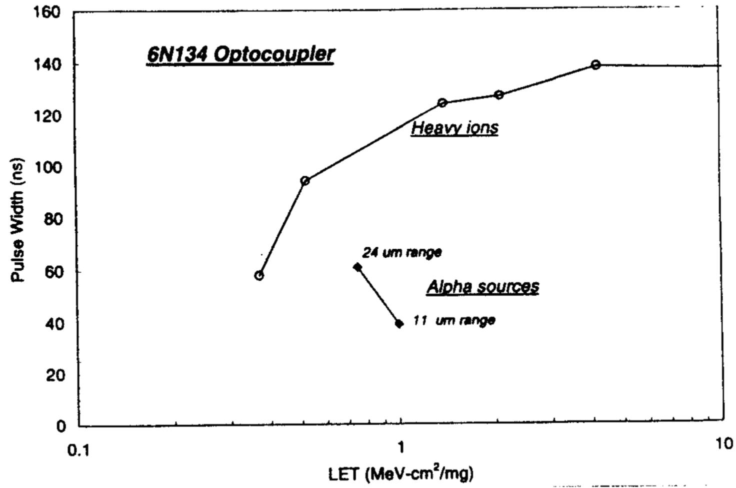


Figure 7. Comparison of Pulse Width of the 6N134 with Long Range Heavy Ions and Short Range Alpha Particles

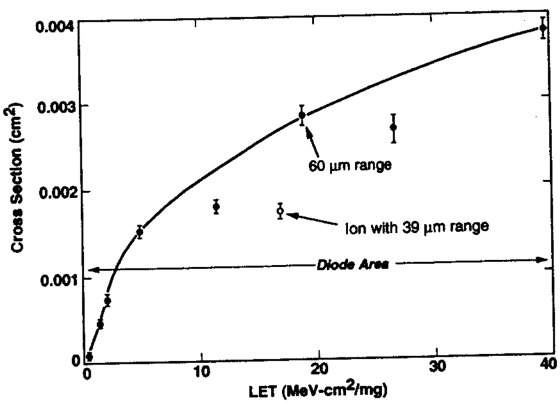


Figure 5. Cross Section vs. LET for the 5203 Optocoupler

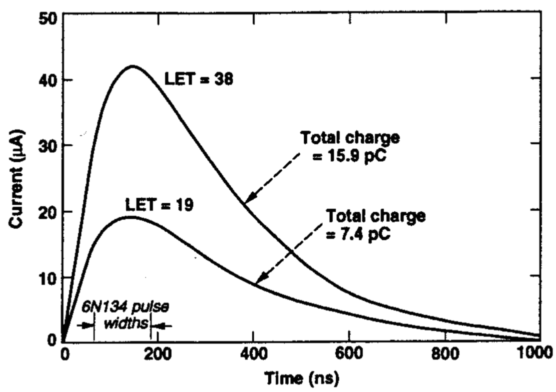


Figure 8. Charge Collection Measurement of the 4N49

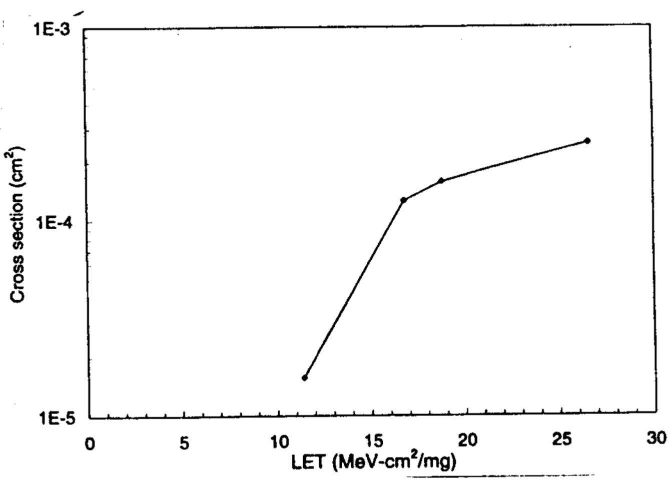


Figure 6. Cross Section vs. LET for the 6N140 Optocoupler (with only a basic transistor amplifer)

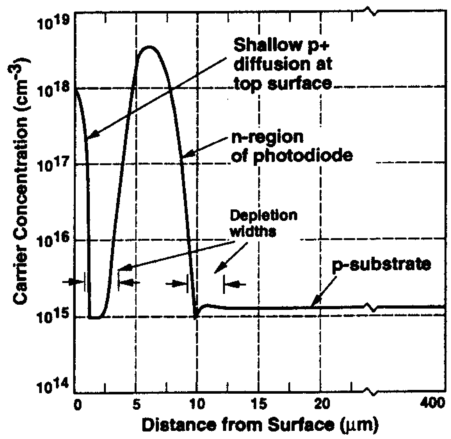


Figure 9. Doping Profile of the 6N134 Photodiode

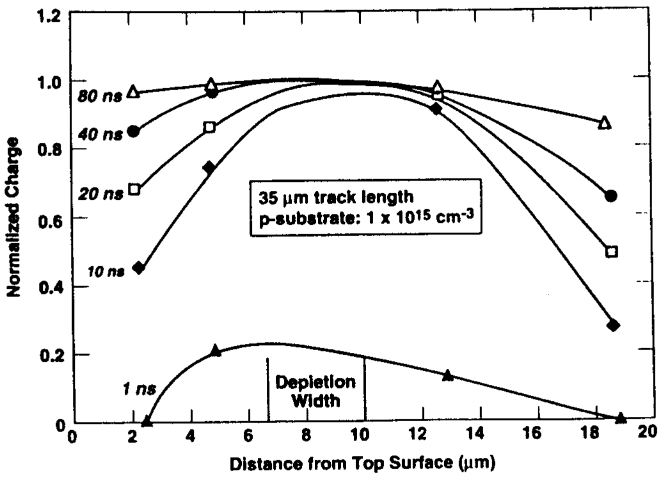


Figure 10. Charge Collection from Short-Range Recoils that Strike Beyond the Depletion Region

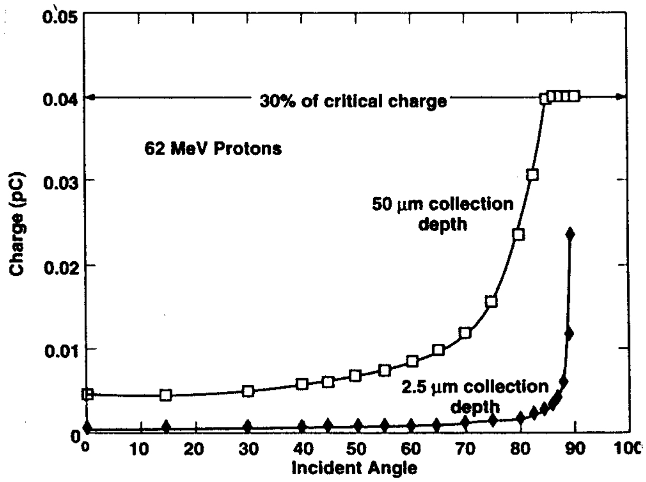


Figure 11. Dependence of Direct Ionization Charge in the Photodiode on Angle for the 6N134 Optocoupler (63 MeV protons)

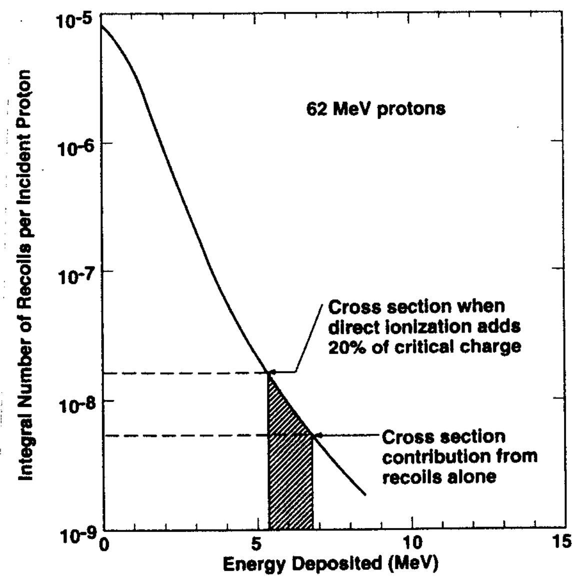


Figure 12. Fraction of Recoils Contributing to Charge Transients with and without Direct Ionization Component